91602
new 82-10 LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

ontario hydro
research division
COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if Reproduced in Whole or in Part

C-14 REMOVAL FROM SPENT IX RESINS PHASE II - PRELIMINARY STUDIES AND PILOT PLANT DESIGN

Report No. 89-54-K

F.H. Chang
Engineer
Process Chemistry Section
Chemical Research Department

ABSTRACT

The laboratory work initiated in Phase I of the study for removing C-14 from spent resins by acid stripping was continued with emphasis on treating laboratory simulated spent resins containing higher activities and actual spent resins from the stations. The results confirmed the effectiveness of the method but indicate the need for further development prior to full scale implementation. A pilot plant study has been proposed. A preliminary process flowsheet has been prepared for the pilot scale operation, and alternative waste disposal schemes have been assessed.

job	file	date	report no.
31-256-462	837.812	May 10, 1989	89-54-K

91602
new 82-10

90-00416/

ontario hydro
research division

EXECUTIVE SUMMARY

C-14 REMOVAL FROM SPENT IX RESINS
PHASE II - PRELIMINARY STUDIES AND PILOT PLANT DESIGN

F.H. Chang
Process Chemistry Section
Chemical Research Department

The radioactive contaminant, carbon-14 (C-14), found in the moderator and the Primary Heat Transport (PHT) systems of CANDU reactors is effectively removed by ion exchangers in the respective purification systems, but disposal of the spent ion exchange resins presents a difficult problem. Because of the unusually long half-life (5730 years) of C-14 and the large volume of resin waste generated, the present practice of long term storage (in quadri-cells) is uneconomical.

A program was initiated in 1987 to develop a process for removing C-14 from the spent resins for separate storage. The objectives were to reduce the storage requirement for C-14 resin waste significantly and to enable disposal of the treated resins as low or intermediate active wastes by shallow land burial at properly designed sites.

Phase I of the program had been completed in 1987, and included a bench-scale laboratory evaluation of several methods selected from the literature. Acid stripping was found to be an effective method, consistently showing removal efficiencies between 98.5% and 100%. Laboratory simulated spent resins with activity levels ranging from 5 to 50 Ci/m^3 were used in the experiments.

Phase II of the study was conducted during 1988 to confirm the efficiency of the acid stripping technique with laboratory simulated spent resins containing higher C-14 activities (200 Ci/m^3) and also with station (actual) spent resin samples retrieved from Pickering NGS. C-14 removal was essentially complete in both cases, but a minute amount of residue, about 0.5% of the total C-14, was found remaining on some actual spent resins after treatment. The residual C-14 was eliminated by further treatment with a strong oxidizing agent.

job	file	date	report no.
31-256-462	837.812	May 10, 1989	89-54-K

The results are encouraging and the process should be developed further for possible plant implementation. Preliminary design calculations at a pilot scale (10-30 liters of resin per batch) indicate potential for significant C-14 waste volume reduction (by a factor of 38). A pilot plant test will be conducted in the subsequent study, and feasibility of full scale operation will be reviewed.

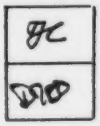


TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	EXPERIMENTAL	2
3.0	RESULTS AND DISCUSSION	3
	3.1 Laboratory Simulated Spent Resins	3
	3.2 Station (Actual) Spent Resins	6
	3.3 Effect of Acid Concentration	9
4.0	PROCESS DEVELOPMENT	9
	4.1 Disposal of Waste By-Products	12
	4.2 Pilot Plant	12
	4.3 Preliminary Process Flowsheets	15
5.0	CONCLUSIONS AND RECOMMENDATIONS	15
REFERENCES		18
APPENDIX A - Experimental Accuracy and Precision		A-1
APPENDIX B - Alternative Schemes for Waste Disposal		B-1
APPENDIX C - Basis for Material Balance		C-1
DISTRIBUTION		last page

9160
nrw 82-10

ontario hydro
research division

To Mr. H.N Isaac
Manager
Nuclear Materials
Management Department

Attn: Mr. L.S. Krochmalnek

C-14 REMOVAL FROM SPENT IX RESINS
PHASE II - PRELIMINARY STUDIES AND PILOT PLANT DESIGN

1.0 INTRODUCTION

The radioactive contaminant, carbon-14 (C-14), is produced mainly in the moderator and Primary Heat Transport (PHT) systems of the CANDU reactors and is effectively removed by ion exchangers in the respective purification systems. The disposal of the spent ion exchange resins is, however, an unresolved problem. Because of the unusually long half-life (5730 years) of C-14 and the large volume of resin waste, the present practice of long-term storage of the bulk resin as C-14 waste is not an efficient disposal method/1, 2, 3, 4/.

A program was initiated in 1987 to develop a process to remove the C-14 from the spent resins for concentration and volume reduction/5/. It was recognized that there was potential for significant reduction in the storage requirement for C-14 waste. The treated resins could then be disposed as intermediate or low level radioactive waste by shallow land burial at properly designed sites.

Phase I of the study was completed in 1987, and included laboratory evaluation of several C-14 removal methods selected from the literature/6, 7, 8, 9, 10/. Laboratory simulated spent resins (i.e., fresh resins equilibrated with C-14 labeled chemicals) at activity levels ranging from 5 to 50 Ci/m^3 were used for the tests. It was found that acid agitation with 6N HCl was an effective method. High removal efficiencies (98.5-100%) were achieved with good reproducibility/11/.

In the (present) Phase II of the study, the laboratory investigation was extended to include treatment of simulated spent resins containing higher C-14 loadings (around 200 Ci/m^3 resin) and also station (actual) spent resin samples retrieved from Pickering NGS. An assessment of the alternative methods for waste disposal, and an estimate of the volume reduction factors for C-14 waste have also been carried out. Preliminary process flowsheets and the design of a pilot plant are also included.

2.0 EXPERIMENTAL

The present set of experiments were designed to accomplish the following:

1) To confirm the removal efficiency at higher levels of C-14 loading (around 200 Ci/m^3) on simulated spent resins.

2) To test the removal efficiency of C-14 with actual spent resin samples retrieved from the stations.

3) To determine the effect of acid concentration on the removal efficiency.

Laboratory simulated spent resin samples were prepared by equilibrating fresh ion exchange resins with a quantity of stock chemical solution of known activity level. The stock solution was prepared by diluting C-14 labeled Na_2CO_3 (supplied by NEN/Du Pont and Amersham) with deionized water. After equilibrating resins (Amberlite IRN 150) with a known quantity of stock solution, the loading of activity on the resins was determined by liquid scintillation counting (LSC) of the solution before and after equilibration. Hionic scintillant (supplied by Canberra-Packard) was used. The resins were loaded to about 200 Ci/m^3 to simulate moderator spent resin at its maximum (observed) C-14 activity level.

For experiments with actual spent resins, two shipments of station resin samples were received and stored at the Radioactive Materials Laboratory (RML) of the Research Division. Sample PI-447 retrieved from a storage tank of Pickering NGS A Unit 2 was received on July 10, 1987; and Sample PI-530 (containers A, B and C) from Pickering NGS A Unit 1 storage tank 502 was received during May 21-25, 1988. The bulk samples were monitored for tritium and gamma fields to ensure that the radiation levels were acceptable for laboratory work in the RML. Smaller samples ranging from 10 to 30 mL were then taken as required for the experiments.

The laboratory apparatus used for acid treatment experiments was the same as that used during Phase I of the study/11/. Briefly, it consisted of a glass flask with magnetic stirring and air sparging. The resin reacted with HCl in the flask and the $^{14}CO_2$ evolved from the reaction was drawn, along with the off-gas, through a water trap (slightly acidified) and two NaOH absorbers. The amounts of C-14 recovered by the absorbers were determined by LSC.

The residual C-14 remaining on the treated resin was determined (by the Analytic Services Section) by total combustion of the resin, followed by recovery of the $^{14}CO_2$ in the combustion off-gas by Carbosorb and determined by LSC.

3.0 RESULTS AND DISCUSSION

3.1 Laboratory Simulated Spent Resins

The results of experiments conducted with resins containing about 200 Ci/m^3 of C-14 are summarized in Table 1.

It can be seen from the results that the residual C-14 on the resins after acid treatment was practically nil in all cases, indicating virtually complete removal of C-14 from the resins.

The recovery of the C-14, evolved as $^{14}CO_2$ in the off-gas, by NaOH absorbers ranged from 99.6 to 102.2% of the original amount on the resins. Although there were discrepancies in the recovery data (eg, 102.2% recovery), they were within the range of normal experimental error and measurement inaccuracies (see Appendix A).

Acid concentrations lower than 6N were used in runs S-1 and S-2, and the removal efficiency was comparable to that obtained with 6N acid during Phase I of the study. The lower volumes of acid and lower aeration rates used in runs S-2 and S-3 also did not seem to affect the removal efficiency.

The reaction times of runs S-1 to S-3 were extended to monitor the progress of the reaction. Samples were taken from the absorbers at 45-minute intervals and analyzed. It can be seen from the results in Table 2 that complete removal was achieved within 45 minutes for runs S-1 and S-3, and 90 minutes for run S-2. Most of the experiments conducted so far with 45 minutes of reaction time yielded satisfactory results.

In summary, the high efficiency of C-14 removal by acid stripping was confirmed for simulated spent resins at high C-14 loadings (200 Ci/m^3) under various experimental conditions. The parametric effects of the experimental conditions such as acid concentration, aeration rate and reaction time could not be determined from the limited results and a more detailed parametric study is recommended. (The effect of acid concentration was further examined in Section 3.3 but the results were still inconclusive).

TABLE 1

SIMULATED SPENT RESIN WITH HIGH C-14 LOADING

(IRN 150 Resin Used per Run = 30 mL, Agitation Speed = 60 rpm)

Run No.	Experimental Conditions						Results								
							First Absorber		Second Absorber		Residual C-14				
											In Spent Acid		On Stripped Resin		
	Acid Conc. (N)	Acid Volume (mL)	Aeration Rate (mL/min)	Reaction Time (min)	C-14 Loading (μCi/mL resin)	Total C-14 Activity (μCi)	C-14 Recovered (μCi)	Percent Recovery (%)	C-14 Recovered (μCi)	Percent Recovery (%)	(μCi)	% of Loading	(μCi/mL)	Total (μCi)	% of Loading
S-1	0.5	125	135	225	204.86	6145.9	6175.5	100.48	3.80	0.06	0.19	.00	.001	0.03	0.00
S-2	2	58	100	225	204.86	6145.9	6283.2	102.23	2.35	0.04	0.17	.00	.002	0.06	0.00
S-3	6	98	100	225	204.86	6145.9	6193.7	100.78	2.56	0.04	0.20	.00	.002	0.05	0.00
S-4	6	125	135	45	240.49	7214.8	7371.8	102.17	0.41	0.01	0.35	.00	.000	0.01	0.00
S-5	6	125	135	45	240.49	7214.8	7182.7	99.55	0.16	0.00	0.04	.00	.000	0.00	0.00

(C21)

TABLE 2

EXTENDED REACTION TIME FOR C-14 RECOVERY

Reaction Time (min)	RUN S-1				RUN S-2				RUN S-3			
	First Absorber		Second Absorber		First Absorber		Second Absorber		First Absorber		Second Absorber	
	C-14 Recovered (μCi)	% Recovery	C-14 Recovered (μCi)	% Recovery	C-14 Recovered (μCi)	% Recovery	C-14 Recovered (μCi)	% Recovery	C-14 Recovered (μCi)	% Recovery	C-14 Recovered (μCi)	% Recovery
45	6175.5	100.48	3.80	0.06	5880.8	95.69	1.87	0.03	6221.2	101.22	2.18	0.04
90	6245.8	101.63	3.93	0.06	6295.0	102.43	2.02	0.03	6298.8	102.49	2.43	0.04
135	6274.2	102.09	3.98	0.06	6283.7	102.24	2.13	0.03	6254.3	101.76	2.48	0.04
180	6250.0	101.69	4.07	0.07	6275.5	102.11	2.21	0.04	6287.2	102.30	2.52	0.04
225	6284.3	102.25	4.12	0.07	6283.2	102.23	2.35	0.04	6193.7	100.78	2.56	0.04

(C21)

3.2 Station (Actual) Spent Resins

To consider for plant application, the effectiveness of the process in treating actual spent resins must also be demonstrated. The sample PI-447 was not useful because the level of C-14 on the resin was too low (less than 2 Ci/m^3). The levels of C-14 loading (7-10 Ci/m^3) on samples PI-530A and PI-530B were still too low to represent moderator spent resins (expected range 50-200 Ci/m^3), but such levels could be considered representative of PHT spent resins (around 5 Ci/m^3). These resins were used in the bulk of the experiments, but additional tests should be conducted when resin samples more representative of moderator spent resins become available.

For a preliminary assessment of the performance at high activity levels, some station spent resins were preloaded with extra C-14 tracers. In four (runs A-9, -10, -14, -15) of the fifteen experiments conducted with station spent resins, the samples were preloaded with additional amounts of $Na_2{}^{14}CO_3$ to raise the total activity level to about 200 Ci/m^3 to simulate moderator spent resin.

The results are summarized in Table 3 and it can be seen that all the runs demonstrated efficient removal of C-14. Only small amounts of residual C-14, which was probably in some organic forms/12/, were detected. They amounted to less than 0.5% of the total C-14 detected on the resins. In runs A-8 and A-10 the stripped resins were further treated with a strong oxidizing agent, potassium persulfate $K_2S_2O_8$/13/, and the residual C-14 was found to be essentially eliminated (only 0.007 Ci/m^3 remained in both cases).

The recovery of $^{14}CO_2$ by the off-gas absorbers was above 99% in all cases. However, the significance of these percentage results requires some clarification. Unlike the laboratory simulated spent resins where a known quantity of C-14 was preloaded onto the resin, the amount of C-14 originally present on the station spent resins was not accurately known. It had to be calculated by summing up the various amounts detected in the absorbing solutions, spent acid and resin residues. It was assumed that this sum represented adequately the total activity originally on the resins; ie, activity balance was assumed to be maintained.

During acid stripping, other gamma-emitting radionuclides on the station spent resin were also removed. The resins and the various solutions of runs A-7 and A-14 were monitored by gamma spectroscopy, and the results are presented in Tables 4 and 5. It can be seen that a significant amount of the gamma-emitting radionuclides was retained in the acid. A much smaller amount was carried over to the water trap but no detectable quantities were found in the alkaline absorbers. The fraction of radionuclides remaining on the resins after acid stripping was still appreciable. The disposal of the treated resin and spent acid as radioactive waste is discussed in greater detail in Section 4.0.

TABLE 3

ACTUAL SPENT RESIN EXPERIMENTS

RUN NO.	RESIN SOURCE[1]	EXPERIMENTAL CONDITIONS[2]			C-14 RECOVERY						RESIDUAL C-14 ON STRIPPED RESIN			TOTAL C-14 ACTIVITY	
					Water Trap		First Absorber		Second Absorber						
		Resin Volume (mL)	Acid Conc. (N)	Acid Volume (mL)	C-14 Recovered (μCi)	Percent of Total (%)	C-14 Recovered (μCi)	Percent of Total (%)	C-14 Recovered (μCi)	Percent of Total (%)	Level of Residual C-14 (μCi/mL)	Total Residual C-14 (μCi)	Percent of Total (%)	Total C-14 Detected (μCi)	C-14 Loading on Resin (μCi/mL)
A-1	PI-447	10.0	6	120	0.002	0.01	18.53	99.51	0.00	0.00	0.009	0.09	0.48	18.62	1.86
A-2	PI-530A	10.4	6	120	0.002	0.00	97.36	99.33	0.36	0.37	0.028	0.29	0.30	98.01	9.42
A-3	PI-530B	10.4	6	120	0.002	0.00	93.41	99.48	0.26	0.28	0.022	0.23	0.24	93.90	9.03
A-4	PI-530C	10.0	6	120	0.002	0.00	71.33	99.15	0.30	0.42	0.031	0.31	0.43	71.94	7.19
A-5	PI-530C	30.0	6	140	0.033	--	324.07	--	0.02	--	NOT ANALYZED		--	*324.12	*10.80
A-6	PI-530A	32.0	6	135	0.023	0.00	319.85	99.70	0.01	0.00	0.029	0.93	0.29	320.81	10.03
A-7	PI-530A	30.0	2	135	0.019	0.00	309.10	99.75	0.01	0.00	0.025	0.75	0.24	309.88	10.33
A-8	PI-530A	32.0	2	135	0.042	0.01	337.51	99.66	0.01	0.00	0.034	1.09	0.32	338.65	10.58
A-9	PI-530B (+5700μCi)	30.0	2	135	0.761	0.01	5854.00	99.95	0.29	0.00	0.062	1.86	0.03	5856.91	195.23
A-10	PI-530B (+5890μCi)	31.0	6	135	1.589	0.03	6074.50	99.93	0.29	0.00	0.086	2.67	0.04	6079.05	196.10
A-11	PI-530B	29.0	6	135	0.085	--	260.13	--	0.01	--	NOT ANALYZED		--	*260.23	*8.97
A-12	PI-530B	29.0	6	135	0.165	0.06	260.90	99.53	0.01	0.00	0.036	1.04	0.40	262.12	9.04
A-13	PI-530B	31.0	6	135	0.031	0.01	276.27	99.34	0.01	0.00	0.058	1.80	0.65	278.11	8.97
A-14	PI-530B (+5700μCi)	30.0	6	135	0.585	0.01	5622.67	99.95	0.16	0.00	0.076	2.28	0.04	5626.70	187.56
A-15	PI-530B (+5700μCi)	30.0	6	135	0.236	0.00	5703.17	99.92	0.29	0.00	0.134	4.02	0.07	5707.72	190.26

[1] These refer to the sample tag numbers described in Sec. 3.2

[2] Reaction time = 45 min., agitation speed = 60 rpm, aeration rate = 135 mL/min for all the runs.

(C21)

TABLE 4
ACID REMOVAL OF GAMMA ACTIVITIES (RUN A-7)
(30 mL of Sample PI-530A)

	BEFORE STRIPPING		AFTER STRIPPING									DISCREPANCY	
	RESIN		RESIN		ACID		WATER TRAP		FIRST & SECOND TRAPS		TOTAL ACTIVITY	ACTIVITY DISCREPANCY	PERCENT DISCREPANCY
ISOTOPE	TOTAL ACTIVITY (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY IN SOLUTION (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	(μCi)	(μCi)	(%)
Co-60	14.76	3.0	5.91	0.3	3.20	0.4	0.001	17.8	-		9.11	5.65	38.3
Cs-134	0.78	6.0	0.36	2.6	0.21	2.7	-	-	-		0.57	0.21	26.9
Cs-137	4.65	3.0	2.22	0.7	0.95	0.7	-	-	-		3.17	1.48	31.8
Mn-54	0.33	7.0	0.15	5.4	0.09	4.1	-	-	-		0.24	0.09	27.3
Zn-65	1.05	1.60	1.47	1.7	0.05	15.1	-	-	-		1.52	0.47	44.8

8

TABLE 5
ACID REMOVAL OF GAMMA ACTIVITIES (RUN A-14)
(30 mL of Sample PI-530B)

	BEFORE STRIPPING		AFTER STRIPPING									DISCREPANCY	
	RESIN		RESIN		ACID		WATER TRAP		FIRST & SECOND TRAPS		TOTAL ACTIVITY	ACTIVITY DISCREPANCY	PERCENT DISCREPANCY
ISOTOPE	TOTAL ACTIVITY (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY IN SOLUTION (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	ACTIVITY ON RESIN (μCi)	PERCENT UNCERTAINTY (%)	(μCi)	(μCi)	(%)
Co-60	15.30	3.0	1.70	6.6	4.25	16.4	0.14	6.7	-		6.09	7.20	60.2
Cs-134	0.57	6.0	0.07	8.8	0.17	17.0	0.26	6.7	-		0.50	0.34	12.3
Cs-137	3.48	3.0	0.43	6.7	1.17	16.5	4.00	6.6	-		5.60	1.34	60.9
Mn-54	0.17	8.0	--	--	0.07	21.8	0.01	16.8	-		0.08	0.28	52.9
Zn-65	0.60	6.0	0.54	6.9	--	--	0.02	13.3	-		0.56	0.85	6.7

(C21)

89-54

3.3 Effect of Acid Concentration

It had been concluded in Phase I of the study that C-14 on spent resins could be effectively removed by acid stripping with 6N HCl, but the effect of using different acid concentrations was not examined/11/.

A search for optimum acid concentration was attempted here by two separate sets of experiments with simulated spent resins. The results in Table 6 were obtained from a direct experimental search over the concentration range from 0.5N to 5N. Acid concentration of 6N was not used because considerable data were already available from the previous work in Phase I/11/.

A second set of experiments was conducted with a sequential lattice search technique/12/. The number of experiments required to search over the same range of 0.5N to 5N was reduced to four, and the results are presented in Table 7.

Both sets of data clearly demonstrated that the C-14 on the resins was practically completely removed; the residual C-14 on the treated resins was negligible in all cases. But the C-14 removed was not totally accounted for, ie, activity balance was not maintained. The recoveries by the gas absorbers averaged 98.5% for the results in Table 6, and 97.5% for those in Table 7. The consistency of these results was inferior to those in Phase I/11/, where the average recovery from 6N HCl treatment was 100.4%, and the activity balance was well maintained. The precision of the present results was, however, quite satisfactory as the variance within each set of data was small. The discrepancies between the removal and recovery data were suspected to be caused by a drift in the stock solution concentration, and it should be more closely monitored in future experiments.

There were no noticeable effect of acid concentration on the removal efficiency. Acid concentrations between 0.5N and 6N were seen to be equally effective. This conclusion is, however, only tentative because activity balance of the data was less than satisfactory. Further investigation should be conducted as part of the parametric study (recommended earlier) for subsequent work.

4.0 PROCESS DEVELOPMENT

To consider the method for practical application, the potential benefits from C-14 waste volume reduction and the overall waste disposal situation need be considered in detail. According to the preliminary process flowsheet to be presented in Section 4.2, a volume reduction factor of 38 may be possible for C-14 waste when a suitable means of fixation is used.

TABLE 6

EFFECT OF ACID CONCENTRATION

RUN NO.	ACID USED		C-14 RECOVERY						RESIDUAL C-14			
			WATER TRAP		FIRST ABSORBER		SECOND ABSORBER		IN SPENT ACID		ON STRIPPED RESIN	
	CONC. (N)	VOL. (mL)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	ACTIVITY (μCi)	PERCENT (%)	ACTIVITY (μCi)	PERCENT (%)
AI-1	0.5	79	0.113	0.004	2535.0	98.41	0.086	0.003	0.037	0.002	<0.01	0.0
AI-2	1.0	79	0.014	0.001	2538.0	98.53	0.039	0.002	0.019	0.001	<0.01	0.0
AI-3	2.0	79	0.017	0.001	2542.2	98.69	0.052	0.002	0.040	0.002	0.01	0.0
AI-4	3.0	79	0.027	0.001	2545.9	98.84	0.080	0.003	0.017	0.001	0.035	0.001
AI-5	4.0	79	0.016	0.001	2529.7	98.21	0.065	0.003	0.012	0.000	<0.01	0.0
AI-6	5.0	79	0.109	0.004	2532.8	98.33	0.057	0.002	0.161	0.006	<0.01	0.0

Notes: Experimental conditions : Resin volume = 50 mL, Initial loading = 51.5 μCi C-14/mL resin, Total activity = 2575.8 μCi, Reaction time = 45 minutes, Agitation rate = 60 rpm, Aeration rate = 135 mL/min

TABLE 7

LATTICE SEARCH FOR OPTIMUM ACID CONCENTRATION

RUN NO.	ACID USED		C-14 RECOVERY						RESIDUAL C-14			
			WATER TRAP		FIRST ABSORBER		SECOND ABSORBER		IN SPENT ACID		ON STRIPPED RESIN	
	CONC. (N)	VOL. (mL)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	C-14 RECOVERED (μCi)	PERCENT OF TOTAL (%)	ACTIVITY (μCi)	PERCENT OF TOTAL (%)	ACTIVITY (μCi)	PERCENT OF TOTAL (%)
AII-1	2.0	79	0.056	0.002	2444.0	97.76	0.069	0.003	0.594	0.024	0.055	0.00
AII-2	4.0	79	0.199	0.008	2435.0	97.40	0.727	0.029	0.104	0.004	0.090	0.00
AII-3	1.0	79	0.031	0.001	2443.8	97.75	0.055	0.002	0.028	0.001	0.10	0.00
AII-4	0.5	79	0.017	0.001	2479.8	97.00	0.044	0.002	0.025	0.001	0.175	0.00

Notes:

1. Experimental conditions are : Resin volume = 50 mL, Reaction time = 45 minutes, Agitation rate = 60 rpm, Aeration rate = 135 mL/min
2. Activity Loadings: Initial Total C-14 Loading = 2500 μCi for all runs except AII-4 where 2556.9 μCi was loaded.

(C21)

4.1 Disposal of Waste By-Products

The main waste by-products are the spent sorbents (solid or liquid) used for recovering the $^{14}CO_2$ evolved, and the spent acid containing the gamma-emitting radionuclides removed from the resin. Three alternative routes for waste disposal (Schemes A, B and C) had been considered and the Scheme A presented in Figure 1 appears to have the greatest potential for practical application. Schemes B and C are less promising and are presented in Appendix B for information.

In Scheme A (see Figure 1), the $^{14}CO_2$ in the off-gas is recovered by solid sorbent $Ca(OH)_2$ /14/, and the spent solids are disposed directly to repository as C-14 waste. The acid is recycled and re-used to the extent possible and is then solidified and disposed as low level active solid waste.

A pilot plant design based on this scheme is discussed in the following section.

4.2 Pilot Plant

A sketch of the pilot plant equipment is shown in Figure 2. The main unit consists of the reactor, the control panel, the piping connections panel and the transfer pumps all premounted on a portable unit. Some auxiliary equipment not shown in the sketch include the off-gas absorber, acid storage tank and holding tanks.

The size of samples used in the laboratory evaluation (10 to 50 mL per run) had to be, for practical reasons, much smaller than the anticipated full scale production of 3 m^3 per batch. An intermediate pilot scale evaluation should be conducted before considering full scale operation. The pilot plant has been designed for processing 10 to 15 liters of dry resins (or up to 30 liters of slurry) per batch which is equivalent to about (1/100)th of the anticipated full production scale.

The pilot plant operation can confirm the design parameters presented in the preliminary process flowsheet given below. It may also uncover potential operational difficulties before the process is tested on a full production scale.

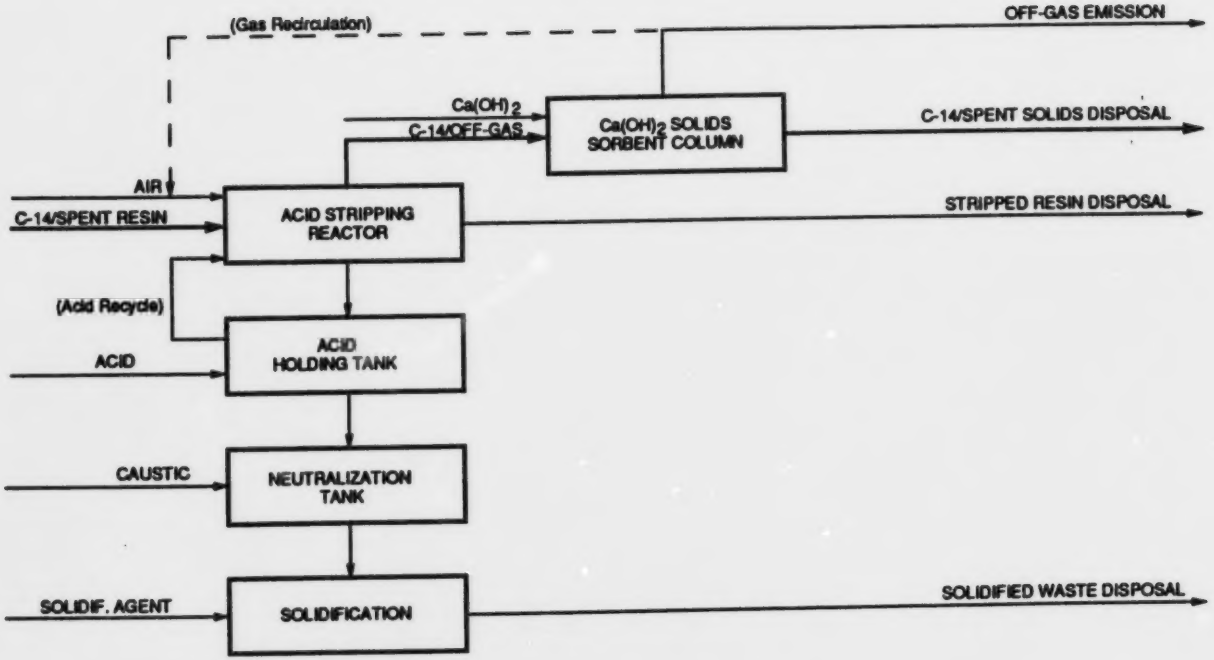


FIGURE 1: SCHEME A FOR WASTE PRODUCT DISPOSAL

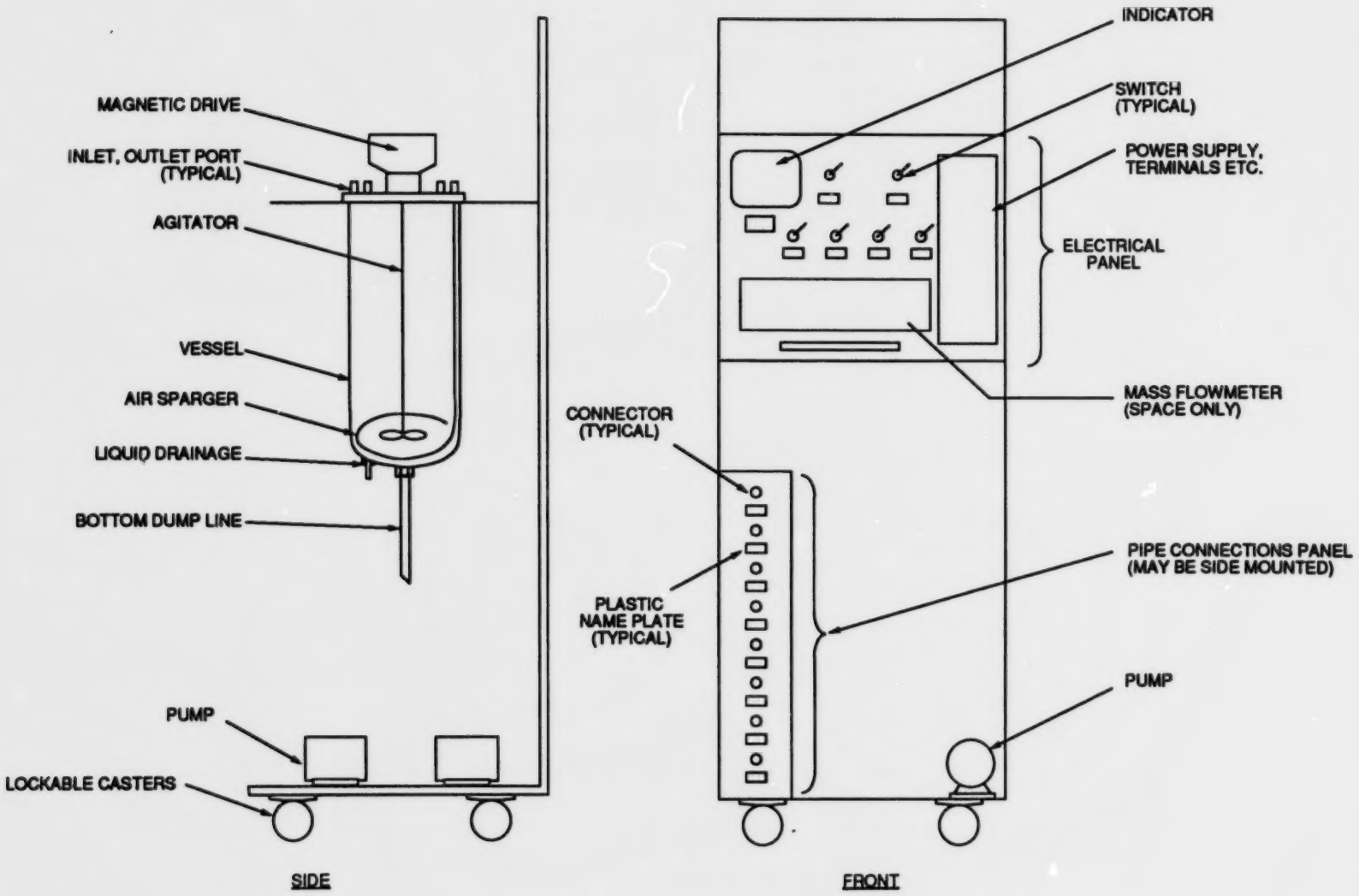


FIGURE 2: SKETCH OF PILOT PLANT ASSEMBLY UNIT

4.3 Preliminary Process Flowsheet

A preliminary process flowsheet and a material balance table for the pilot scale operation have been developed based on the waste disposal scheme A presented above. The basis for the calculations is outlined in Appendix C.

The process flowsheet and the corresponding material balance table are given in Figure 3. The material balances were calculated based on a pilot scale processing rate of one batch of spent resin per 45 minutes. Ten liters of dry resin containing 200 Ci/m^3 of C-14 activity will be processed per batch. In addition to radioactive C-14, 0.2 meq/mL of inactive carbonate was assumed to be present on the resin. The CO_2 concentration in the ambient air used for air sparging was assumed to be 330 ppm.

The initial concentration of the acid was 6 N, but the concentration would decrease as the spent acid was reused. After 20 batches, the concentration of the spent acid would be about 1.5 N, and the acid would then be neutralized with 10 N NaOH before being solidified for ultimate disposal. The volume increase upon solidification was estimated approximately to be two fold.

The C-14 and inactive carbon evolved as CO_2 was removed by passing the off-gas through a $Ca(OH)_2$ sorbent column. The solid sorbents were assumed to be 90% pure and sorbent utilization was assumed to be 80% /15/. The spent solids containing the C-14 could be disposed to waste repository directly. It was estimated that the volume of C-14 waste could be reduced from 10 liters to about 0.26 liters, yielding a volume reduction of about 38.

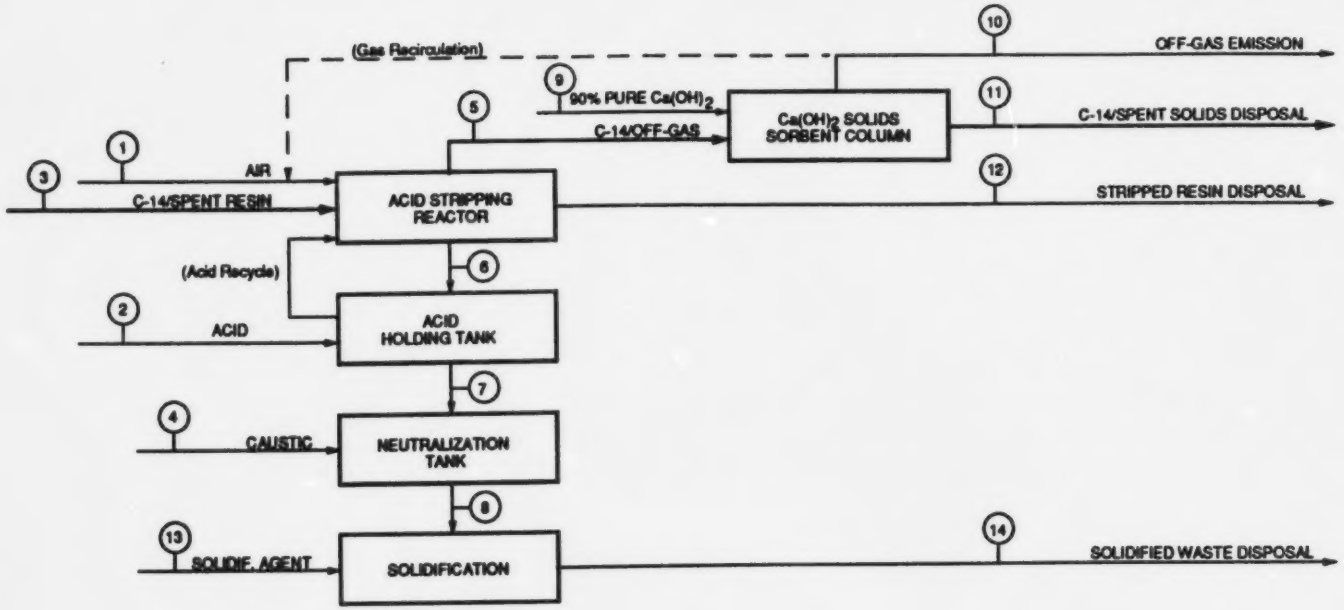
Additional volumes of solid wastes from treated resins and spent acid would result, but these can be disposed of less expensively by shallow land burial. The volume of spent acid after solidification amounts to 0.8 times the original resin volume, and the treated resin (10 liters) volume would amount to about 20 liters upon immobilization.

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. The high efficiency of C-14 removal by acid stripping with HCl determined previously at low activity levels (up to 50 Ci/m^3) with laboratory simulated spent resins has been confirmed at the higher level of 200 Ci/m^3. The removal was essentially 100%.

2. The removal of C-14 from station (actual) spent resins by acid stripping was also highly efficient (over 99%). However, only resins with low activities (up to 10 Ci/m^3) resembling PHT spent resins were tested. Additional tests should be conducted when resins more representative of moderator spent resins with higher levels of C-14 become available.

3. A pilot scale evaluation is recommended. Basis for sizing full scale equipment can be established, and potential operational problems may be uncovered by pilot plant operation.



	STREAM / COMPONENT	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭
GAS (l/min)	N_2 & O_2	44.985				44.985					44.985				
	CO_2	0.015				0.513									
	$^{14}CO_2$					0.015									
	HCl					0.012									
	H_2O					0.626									
	TOTAL	45.000				46.151					44.985				
LIQUID (g/batch)	HCl		3066.0				2989.9	77.20							
	NaOH				84.60										
	NaCl								123.73						123.73
	H_2O		12306.0		196.2		12301.9	611.22	845.49						845.49
	TOTAL		15372.0		280.8		15291.8	688.42	969.22						0.89 liters
SOLID (g/batch)	$Ca(OH)_2$									101.95		19.88			
	$CaCO_3$											103.14			
	$Ca^{14}CO_3$											3.01			
	$CaCl_2$											1.39			
	H_2O											42.16			
	IX RESIN			10.0 liters									10.0 liters		
	IMPURITIES									11.33		11.04		0.89 liters	0.89 liters
	SOLIDIF. AGENT														
	TOTAL			10.0 liters[1]						113.28		180.62[2]	10.0 liters[3]	0.89 liters	1.78 liters

BASIS: PILOT PLANT SCALE (10 LITERS DRY RESIN PER BATCH EVERY 45 MINUTES)

NOTES: 1. Containing 2.03 meq/ml carbonates (active and inactive)
2. About 0.26 liter in volume
3. Containing 2.03 meq/ml chlorides

FIGURE 3: PROCESS FLOWSHEET WITH WASTE DISPOSAL SCHEME A

176822 8111 RD

4. A process flowsheet and a material balance table have been developed at the pilot scale. The recovery of C-14 by solid sorbents for direct disposal appears to be more efficient. It is estimated that the volume of C-14 waste can be reduced by a factor of 38. These projections have to be verified by pilot scale tests.

5. A bench-scale study of the effects of the operating parameters should also be conducted to establish the operating conditions for the pilot scale operation.

Approved by:

D.J.R. Dodd
Manager
Chemical Research Department

Prepared by:

F.H. Chang
Engineer
Process Chemistry Section

Reviewed by:

B.R. Nott
Unit Head
Water Research Unit
Process Chemistry Section

REFERENCES

1. Kabat, M.J. and Gorman, D.J., "Carbon-14 in Ontario Hydro's Nuclear Stations: Production, System and Effluent Levels, Dosimetry, Environmental Data," Ontario Hydro Safety Services Dept., Information Report, SSD-1R-80-3 (1980).

2. Maruska, R.W., "A Correlation of Measured Carbon-14 EMissions and Station Operating Parameters," Ontario Hydro Nuclear Generation Division Report No. RMEP-IR-03483-01 (Nov. 1981).

3. van Berlo, J.P., "The Production and Release of Carbon-14 from the CANDU 600 Reactor," AECL Memo File No. 35-07000-400-000/91-79000-200000 (Nov. 5, 1981).

4. Khan, T.A., "Carbon-14 Management Project Status Review 1984," Ontario Hydro Design and Development Division Report No. 84259 (June, 1984).

5. Krochmalnek, L.S., "IX Resin Treatment Research Program," Ontario Hydro Nuclear Materials Management Dept. Memo. (Jan. 9, 1987).

6. Buckley, L.P., "Removal of Carbon-14 from Ion-Exchange Resin," AECL PR-FM-63P (p. 5-19).

7. Bonnici, P., Cohylakis D. and Leidner, J., "Stripping of C-14 Activity from Ion Exchange Resins," Ontario Research Foundation, Dept. of Materials Chemistry, Interim Report No. 4 (nov. 19, 1980).

8. Nott, B.R., "Acid Stripping of Ion Exchange Resins for Carbon-14 Removal," Ontario Hydro Research Division Report No. 78-345-K (Dec. 1, 1978).

9. Nott, B.R., "Acid Stripping of Ion Exchange Resins for Carbon-14 Removal: Phase II," Ontario Hydro Research Division Report No. 79-495-K (Oct. 16. 1979).

10. Nott, B.R., "Determination of Carbon-14 in Spent Ion Exchange Resins," Int. J. Appl. Radiant, Isotope, Vol. 33, pp. 584-585, (1982).

11. Chang, F.H., "C-14 Removal from Spent IX Resins Phase I - Laboratory Evaluation of Methods," Ontario Hydro Research Division Report No. 88-120-K (Aug. 18, 1988).

12. Greening, F.R., "Sodium Hydroxide Interferences in the Determination of Carbon-14 by Liquid Scintillation Counting (LSC)," Ontario Hydro Research Division Report No. 79-21-K (Jan. 25, 1979).

13. Wilde, D.J., "Optimum Seeking Methods," P. 28, Prentice-Hall, 1964.

14. Knowles, G.K., "Carbon-14 in Reactor Plant Water," 23rd Conference on Analytic Chemistry in Energy Technology, Gotlinburg. Tenn. (Oct. 9-11, 1979).

15. Cheh, C.H. and Glass, R.W., "$^{14}CO_2$ Removal from Moderator Cover Gas," Ontario Hydro Research Division Report No. 82-342-H (Oct. 13, 1982).

16. Qureshi, R.M., "Counting of Natural Carbon-14 for Hydrological Studies Using a Commercailly Available CO_2 Absorber," MSc Thesis, Appendix B, University of Waterloo, Ontario, Canad. (1982).

17. Currie, L.A., "Limits for Qualitative Detection and Quantitative Determination - Application to Radiochemistry," Analytical Chemistry, Vol. 40, No. 3, pp. 586-593 (March, 1968).

18. Sood, S., and Chang, F.H., Private Communication.

APPENDIX A

Experimental Accuracy and Precision

INTRODUCTION

The amounts of C-14 expressed in the experimental results were determined not from gravimetric measurements but rather by inference from radioactive decay data. Activity decay is inherently a stochastic process subject to random errors/16, 17/. The measurement procedure also involves many steps of sample preparation which may introduce errors from inaccuracies in apparatus, sample composition, calibration standards as well as from human errors.

The accuracy and precision of the results in the present study are assessed in detail below to gain an appreciation of the significance and reliability of the results.

ACCURACY

Accuracies of experimental data are inherently limited by the accuracy of the instruments and apparatus used; most notably in the present study are that of the liquid scintillation counter and the glasswares. In the present experiments, the accuracy of counting is estimated to be 5% /17/ based on the accuracy of the certified standard solution (3%) used for instrument calibration and the calibration accuracy of the counter (2%). The accuracy of volumetric measurements is estimated to be 1% based on glassware supplier's specifications. The accuracy of the weighing balance is 0.005 g.

Based on the above information and the number of experimental steps involved, the maximum cumulative inaccuracy for the acid stripping experiments is estimated to be about 10%. In practice, the accuracy of the experimental data is likely to be better.

The accuracy of the experimental data is also affected by the experimenter's human errors, which could sometimes lead to consistent but biased results. Results obtained with good precision may not be accurate. Such inaccuracies are difficult to detect. It would require careful interpretation of the experimental data, for example, by verifying the overall material or activity balances. In the present study, such analysis was carried out for the data in Tables 6 and 7 (Section 3.3), which were obtained with good precision, to find that the data were in fact inaccurate, probably due to a drift in stock solution concentration.

PRECISION

Precision of experimental results can be more readily quantified. Three different groups of results are analyzed below:

(a) Overall Recovery Data

Repeated experiments under supposedly identical conditions may yield different results. The supposedly identical conditions may deviate due to inexactness in human operations, drifts in instrumental settings or chemical instabilities. These sources of error affect the overall precision of the results and can be quantified by the standard deviation of the data.

The efficiency of the resin treatment process was evaluated in terms of the percent recovery of the C-14 originally on the resin by the absorbing solution. A set of recovery data obtained in Phase I of the study/11/ is reiterated below in Table A-1:

TABLE A-1

Precision in the Overall Recovery Data

Experimental Conditions:

Resin Volume	- 10 mL of IRN 150
Acid Concentration	- 6N HCl
Acid Volume	- 120 mL
Reaction Time	- 45 minutes
Agitation Speed	- 60 rpm

Results:

The percent recoveries of C-14 from simulated moderator spent resin at 50 Ci/m^3 loading in 10 trials under identical conditions were:

(1)	99.90%
(2)	100.02%
(3)	102.20%
(4)	98.56%
(5)	101.46%
(6)	99.36%
(7)	100.31%
(8)	102.65%
(9)	99.45%
(10)	99.70%

Statistical Data:

Mean recovery efficiency	- 100.35%
Variance, s^2	- 1.7645
Standard Deviation, s	- 1.3285
s %	- 1.32%

It can be seen that with carefully executed experiments, the standard deviation was around 1.32%, which compares favourably with the previously estimated overall accuracy of about 10%.

(b) Sample Preparation

To measure C-14 content in the various solutions, samples have to be prepared for liquid scintillation counting (LSC). The precision of volumetric and gravimetric measurements and the effects of scintillant would all affect the measurement results.

Ten identical samples were prepared from the liquid solutions (water trap and absorbers) of the experimental runs A-6, A-7, A-8 and A-11 in the present study to evaluate the precision in sample preparation. From the counting results in Table A-2, it can be seen that the variations in these measurements are larger than the theoretical percent deviations claimed for the counter. But the experimental s% is generally better than the estimated counting accuracy of 5% (except for water trap of run A-8).

TABLE A-2

Consistency in Sample Preparation

Run No.	Source of Sample	Results of Counting 10 Samples from Same Source: Mean X	St. Dev s	2s%	Instrument Precision[1] 2s%
A-6	Water Trap	0.19	0.007	7.37	4.46-4.52
	Absorber 1	68.86	0.26	0.81	0.24
	Absorber 2	0.69	0.02	5.80	2.34-2.37
A-7	Water Trap	0.15	0.006	8.00	3.45-3.64
	Absorber 1	61.82	0.18	0.58	0.19-0.20
	Absorber 2	0.36	0.005	2.78	2.30-2.34
A-8	Water Trap	0.33	0.022	13.33	7.22-2.86
	Absorber 1	67.50	0.18	0.53	0.53
	Absorber 2	0.47	0.02	8.51	6.24-6.64
A-11	Water Trap	0.85	0.015	3.53	1.48-1.51
	Absorber 1	26.01	0.07	0.54	0.27
	Absorber 2	0.53	0.007	2.64	1.89-1.92

Note [1] : Output from counter, indicating theoretical limit of precision at the given activity level.

(c) Counting

Repeated counting of the same sample may yield different measurements due to random measurement errors. Nuclear disintegration is inherently a random process, and therefore determination of C-14 content by scintillation counting of beta emissions is particularly susceptible to random fluctuations.

Samples prepared in runs A-6, A-7, A-8 and A-11 were counted repeatedly. The results shown in Table A-3 indicates that, in general, the standard deviations of counting are comparable to the precision limits specified by the instrument.

By comapring the precision of the results in Table A-2 to that in Table A-3, it can be observed that the experimenter has maintained the same degree of precision as that obtainable from the instrument.

TABLE A-3

Precision of Counting Measurement

Run No.	Source of Sample	Sample No.	Results of Counting Same Sample 10 Times Mean X	St. Dev s	2s%	Instrument Precision [1] 2s%
A-6	Water Trap	(a)	0.18	0.011	12.22	9.86-11.06
		(b)	0.19	0.007	7.37	9.84-10.31
	Absorber 1	(a)	63.96	0.17	0.53	0.54
		(b)	63.78	0.25	0.78	0.54
	Absorber 2	(a)	0.69	0.02	5.80	5.15-5.37
		(b)	0.69	0.01	2.90	5.23-5.35
A-7	Water Trap	(a)	0.14	0.01	14.29	11.04-12.34
		(b)	0.15	0.008	10.67	11.08-12.29
	Absorber 1	(a)	61.85	0.23	0.74	0.55
		(b)	61.76	0.22	0.71	0.55
	Absorber 2	(a)	0.36	0.014	7.78	7.14-7.52
		(b)	0.36	0.012	6.67	7.28-7.58
A-8	Water Trap	(a)	0.034	0.009	4.71	7.35-7.72
		(b)	0.32	0.010	6.25	7.60-8.05
	Absorber 1	(a)	67.55	0.16	0.47	0.53
		(b)	67.52	0.25	0.74	0.52-0.53
	Absorber 2	(a)	0.47	0.02	8.51	6.23-6.50
		(b)	0.47	0.01	4.26	6.28-6.50
A-11	Water Trap	(a)	0.85	0.013	3.06	3.30-3.37
		(b)	0.83	0.016	3.86	3.31-3.44
	Absorber 1	(a)	26.04	0.062	0.48	0.60
		(b)	26.06	0.072	0.55	0.60
	Absorber 2	(a)	0.52	0.013	0.05	4.23-4.37
		(b)	0.52	0.015	5.77	4.21-4.41

Note [1] : Output from counter, indicating theoretical limit of precision at the given activity level.

CONCLUSION

Although the precision of the experiments appears to be satisfactory, the accuracy, or rather, inaccuracy of the measurement technique remains a concern. The conservatively estimated overall inaccuracy of 10% is large relative to the low level of residual activity (less than 1% of original C-14) to be determined.

It is recommended that the residual C-14 on the treated resin be determined directly, eg, by combustion of the treated resin and analysis of the off-gas. The alternative method of determining this quantity by subtracting the C-14 detected in the absorbing solution from the original C-14 loading on the resin to arrive at a residual amount of less than 1% of the original amount may not yield meaningful results. The two original measurements are each subject to potential inaccuracies of around 10%.

Secondly, wherever possible, the experiments should be repeated until the results are statistically significant. Significance levels of the data should be assessed. Statistical experimental design methods should be employed to minimize the number of experiments required for drawing statistical conclusions.

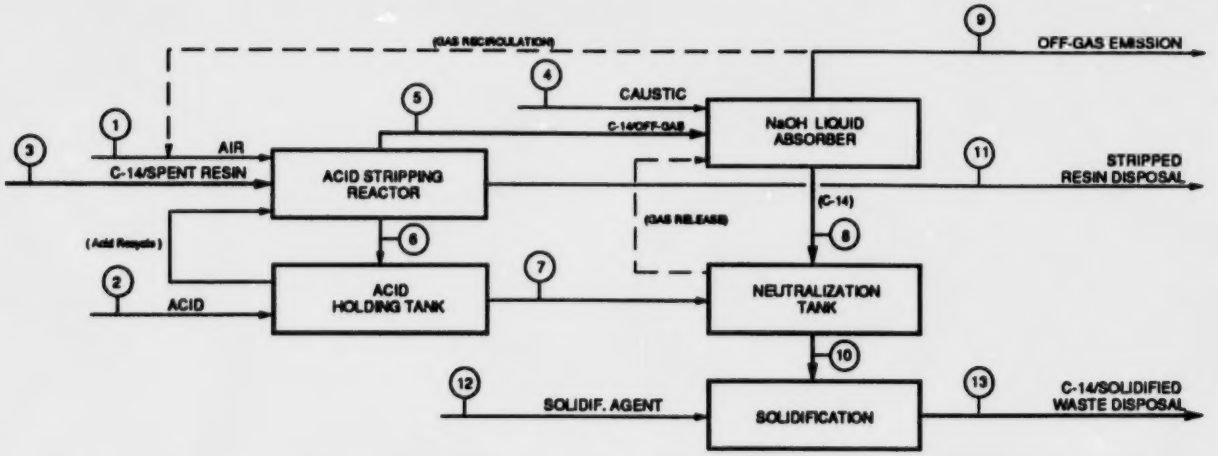
APPENDIX B

Alternative Schemes for Waste Disposal

In additional to the waste disposal Scheme A presented in Section 4.1, the following two alternative routes have also been considered, but these are not as promising and will not be pursued further.

Scheme B (see Figure B-1): Recover the $^{14}CO_2$ by liquid sorbent (NaOH solution). Neutralize the spent caustic with spent acid and solidify the mixture solution for disposal as C-14 waste. This scheme was considered too risky because of the potential for release of $^{14}CO_2$ from the sorbent under acidic conditions of the mixture; also the stability of C-14 in the solidified matrix might pose some concern.

Scheme C (see Figure B-2): Recover the $^{14}CO_2$ by solid gas sorbent and store/dispose the spent sorbent as C-14 waste. Pass the spent acid through the treated resin until the radionuclides in the spent acid are sufficiently reduced to enable disposal of the acid as regular industrial waste. The spent resin containing only gamma-emitting radionuclides can be disposed of by shallow land burial. This scheme was abandoned after some preliminary experimentation with spent acid. The spent acid was passed through a column of treated resin. The resin selectivity for (re)sorption of the radionuclides was adjusted by adding LiOH to the spent acid. As shown by the results in Table B-1, the best removal was achieved at pH 7. However, the fraction (30%) of radionuclides remaining in the acid was still too high, and this scheme was not pursued further.



	STREAM / COMPONENT	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
GAS (mol/hr)	N_2 & O_2	44.985				44.985				44.985				
	CO_2	0.015				0.513								
	$^{14}CO_2$					0.015								
	HCl					0.012								
	H_2O					0.626				1.296				
	TOTAL	45.000				46.151				46.281				
LIQUID (gram)	HCl		3068.0				2968.9	77.20						
	NaOH				180.0				94.14		9.54			9.54
	Na_2CO_3								109.24		109.24			109.24
	$Na_2{}^{14}CO_3$								3.19		3.19			3.19
	NaCl								1.48		125.20			125.20
	H_2O		12306.0		417.5		12301.9	611.22	412.77		1062.06			450.84
	TOTAL		15372.0		597.5		15291.8	688.42	620.81		1309.23[2]			1.22 liters
SOLID (gram)	$Ca(OH)_2$			10.0 liters[1]								10.0 liters[3]		
	IX RESIN												1.22 liters	1.22 liters
	IMPURITIES													
	SOLIDIF. AGENT													
	TOTAL			10.0 liters									1.22 liters	2.44 liters

BASIS: PILOT PLANT SCALE (10 LITERS DRY RESIN PER BATCH EVERY 45 MINUTES)

NOTES: 1. Containing 2.03 meq/ml carbonates (active and inactive)
2. About 0.26 liter in volume
3. Containing 2.03 meq/ml chlorides

FIGURE B-1: WASTE DISPOSAL SCHEME B FLOWSHEET

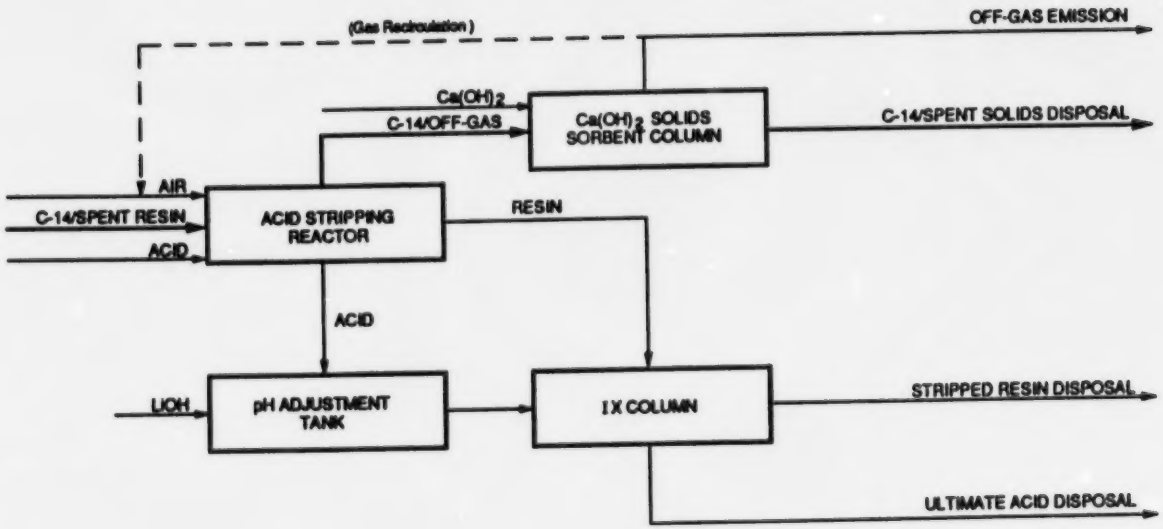


FIGURE B-2: SCHEME C FOR WASTE PRODUCT DISPOSAL

TABLE B-1

SPENT ACID RE-PROCESSING

Source of Acid and Resin	Run A-11			Run A-12			Run A-6		
Acid pH	pH 3			pH 7			pH 11		
Activities in Acid	Before (μCi/mL)	After (μCi/mL)	Percent Removal (%)	Before (μCi/mL)	After (μCi/mL)	Percent Removal (%)	Before (μCi/25mL)	After (μCi/25mL)	Percent Removal (%)
Co-60	2.06×10^{-2}	9.28×10^{-3}	55.0	3.15×10^{-2}	7.70×10^{-3}	75.6	8.11×10^{-1}	3.19×10^{-1}	60.7
Cs-134	7.91×10^{-4}	5.09×10^{-4}	35.7	1.27×10^{-3}	3.59×10^{-4}	71.7	4.11×10^{-2}	2.60×10^{-2}	36.7
Cs-137	5.40×10^{-3}	2.38×10^{-3}	55.9	8.69×10^{-3}	2.63×10^{-3}	69.7	2.25×10^{-1}	1.63×10^{-1}	27.6
Mn-54	3.50×10^{-4}	1.30×10^{-4}	62.9	5.19×10^{-4}	1.42×10^{-4}	72.6	2.18×10^{-2}	2.96×10^{-3}	86.4

(C21)

APPENDIX C

Basis for Material Balance

GENERAL OPERATING PARAMETERS AND CONDITIONS:

Processing Rate	- 45 minutes per batch
Size of Batch	- 10 liters dry resins per batch
Temperature	- 20°C
Pressure	- atmospheric

CONDITIONS OF MAIN STREAMS:

1. Air Stream
   - Aeration Rate - 45 liters/minute
   - Composition - 330 ppm CO_2; the remaining inert gases assumed to be N_2 & O_2

2. Acid Stream
   - Concentration of HCl Solution - 6 N (approximately 20% wt).
   - Density of HCl Solution - 1.098 g/ml
   - Partial Pressure of HCl over Solution - 10.3 mm Hg
   - Partial Pressure of H_2O Over Solution - 0.205 mm Hg

3 Resins
   - Void Factor of Dry Resin - 0.4
   - Composition of Resin Slurry - 50% weight of liquid (acid)
   - C-14 Carbonate on Resin - 0.006 meq/mL (200 Ci/m^3)
   - Inactive Carbonate on Resin - 0.2 meq/mL

4. Caustic
   - Concentration of NaOH Solution - 10 N (approximately 30% wt)
   - Density of 10 N NaOH Solution - 1.3277 g/ml (20°C)

5. Solid Sorbents
   - Bulk Density of 90% Pure $Ca(OH)_2$ - 0.43 g/ml (experimental data)
   - Bulk Density of spent $Ca(OH)_2$ solids - 0.70 g/ml (estimated)

6. Liquid Waste
   - Density after neutralization (Scheme A) - 1.092 g/ml (estimated)
   - Density after neutralization (Scheme B) - 1.070 g/ml (estimated)